

On the Lubrication of Heavily Loaded Surfaces With Special Reference to Solidification of the Lubricant

by

BO JACOBSON

LUND 1972

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ELANDERS BOKTRYCKERI AKTIEBOLAG

1972

On the Identification of Heavy
Landed Species With Special
Reference to Solidification
of the Lubricant



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The following papers are included in this dissertation:

1. "On the Lubrication of Heavily Loaded Spherical Surfaces Considering Surface Deformations and Solidification of the Lubricant".
Bo Jacobson. Acta Polytechnica Scandinavica, Mechanical Engineering Series No 54, Stockholm 1970.
2. "Elasto-Solidifying Lubrication of Spherical Surfaces". Bo Jacobson, ASME Paper No. 72-Lub-7. 1972.
3. "On the Lubrication of Heavily Loaded Cylindrical Surfaces Considering Surface Deformations and Solidification of the Lubricant".
Bo Jacobson. ASME Paper No. 72-Lub-44. 1972.



Elanders Boktryckeri Aktiebolag
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Lubrication of Heavily Loaded Surfaces

The pressure build-up in a thin Newtonian oil film between two moving surfaces is given by the partial differential equation

$$\frac{\partial}{\partial x} \left(\frac{\rho h^3}{\eta} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(\frac{\rho h^3}{\eta} \frac{\partial p}{\partial z} \right) = 6(U_1 + U_2) \frac{\partial}{\partial x} (\rho h)$$

which was published in 1886 by Reynolds (6).

In this equation

- x, z = coordinates
- ρ = oil density
- h = oil film thickness
- η = oil viscosity
- p = oil film pressure
- U_1, U_2 = surface velocities

Reynolds' equation can only be used at relatively low pressures because of the solidification phenomenon. At a certain pressure, the solidification pressure, the oil converts from a liquid to a solid. The solidification pressures are different for different oils and depending on the temperature. More complicated oil molecules give lower solidification pressure, and rising temperature gives rising solidification pressure. In the calculations of this thesis, the solidification is supposed to be instant, i.e. the pressure increase to convert the oil from a liquid to a solid is zero at the solidification pressure. This is a good approximation, as the real pressure interval between liquid and solid oil is only one or two per cent of the maximum pressure in the contact. The solidified oil behaves as usual solid materials, i.e. it has a limited shear strength. This limited shear strength makes the steep pressure drop at the outlet of the contact, predicted by Grubin (1), Petrusevich (5), and others, impossible, see reference (2, 3, 4). Instead, the maximum pressure derivative is given by

$$\left(\frac{\partial p}{\partial x} \right)^2 + \left(\frac{\partial p}{\partial z} \right)^2 = \frac{4\tau_s^2}{h^2}$$

where τ_s = the shear strength of the solidified oil.

This equation gives the pressure build-up in the sliding solidified zone.

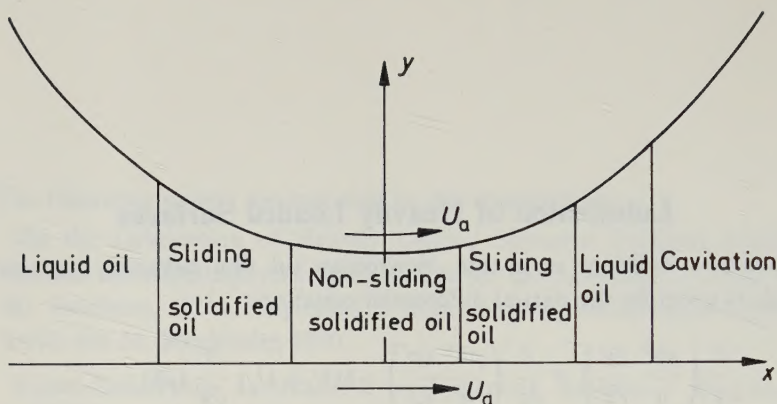


Fig. 1. Section of the oil film.

In the part of the contact, where the pressure derivative isn't big enough to make the shear stress reach the shear strength, the pressure build-up is given by

$$p - p_{SE} = \frac{h_{SE} - h}{h_{SE}} \cdot \frac{\Delta p}{\Delta v}$$

where p_{SE} = the pressure at the inlet of the non-sliding zone

h_{SE} = the oil film thickness at the same point

$\Delta p / \Delta v$ = the stiffness of the solidified oil.

At the boundaries between the liquid oil and the solidified oil, between the sliding and non-sliding solidified oil and at the cavitation boundary, the continuity of mass has to be satisfied.

The boundary between liquid and solidified oil is given by the equation

$$\frac{dz}{dx} = \frac{\frac{h^2}{12\eta} \frac{\partial p}{\partial z} + (U - U_a) \frac{\partial p / \partial z}{\partial p / \partial x}}{\frac{h^2}{12\eta} \frac{\partial p}{\partial x} + U - U_a}$$

For the two dimensional case, part 3, this equation can be simplified to

$$U_a - \frac{h^2}{12\eta} \frac{\partial p}{\partial x} = U$$

where

$$\rho h U = \rho_E h_E U_a$$

where

U_a = surface velocity in the x -direction

U = solidified oil velocity in the x -direction

ρ_E = oil density in the non-sliding solidified region

h_E = oil film thickness at the same point.

The boundary between sliding and non-sliding solidified oil is determined by the condition

$$U = U_a, \quad W = 0$$

where W = solidified oil velocity in the z -direction.

The boundary between the liquid oil zone and the cavitation zone is given by

$$p = 0 \quad \text{for} \quad \frac{\partial p}{\partial x} = \frac{\partial p}{\partial z} = 0$$

In the numerical calculations for part 3 the inlet boundary condition is $p = 0$ at $x = -2a$ where $2a$ = the Herzian width. In the part 1 and 2 the inlet boundary condition is $p = 0$ at $x = -2a$ and $z = \pm 2a$.

In the calculations the oil and surface properties are constant. The liquid oil compressibility $\delta = 6 \times 10^{-10} \text{ m}^2/\text{N}$, the shear strength of the solidified oil $\tau_s = 15 \times 10^6 \text{ N/m}^2$, the solidification pressure $p_s = 10^8 \text{ N/m}^2$, and the constant in the viscosity expression $B = 5.1 \times 10^{-9} \text{ m}^2/\text{N}$. In paper 1 the solidified oil stiffness is $\Delta p/\Delta v = 2.7 \times 10^{11} \text{ N/m}^2$ and the surface property $k = 5.5 \times 10^{-12} \text{ m}^2/\text{N}$. In papers 2 and 3 the solidified oil stiffness is $\Delta p/\Delta v = 2 \times 10^{11} \text{ N/m}^2$, and $k = 2.8 \times 10^{-12} \text{ m}^2/\text{N}$.

Figs. 2 to 4 show theoretical oil film thicknesses and theoretical pressure fields for one spherical and one cylindrical contact.

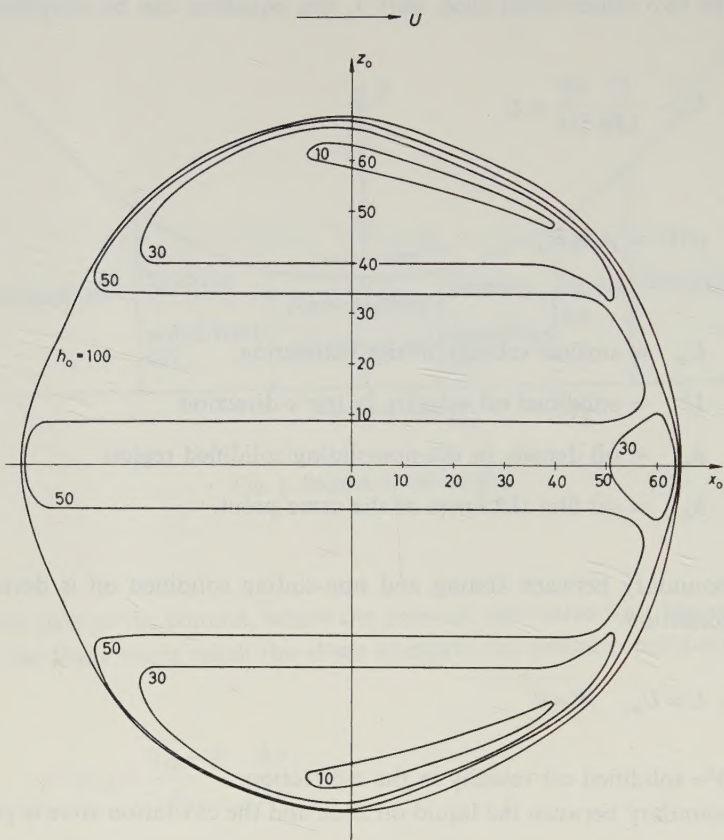


Fig. 2. Theoretical height function for $P_0=10,000$, $k_0=10$, $\delta_0=0.960$, $\tau_{0s}=20.7$, $p_{0s}=0.0625$, $(\Delta p/\Delta v)_0=125$, $B_0=8.15$, $\Gamma_0=3745$, $E_0=2150$.

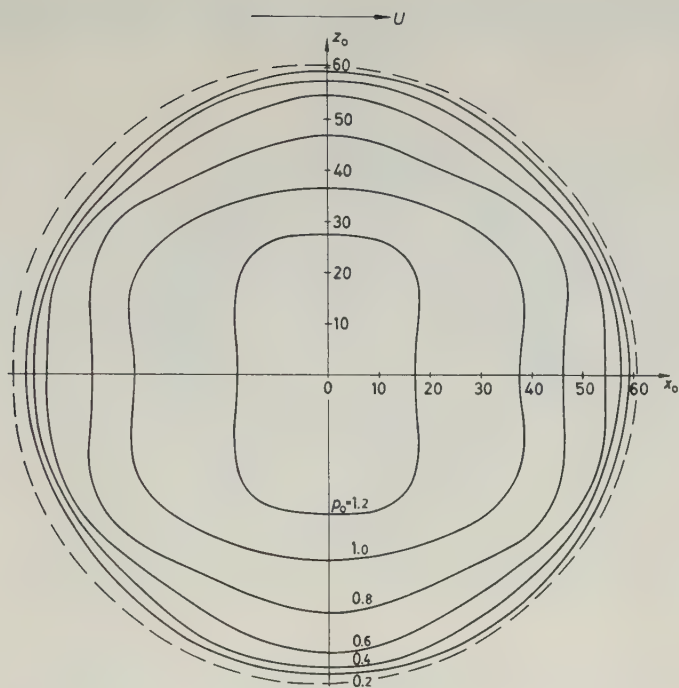


Fig. 3. Theoretical pressure field for $P_0=10,000$, $k_0=10$, $\delta_0=0.960$, $\tau_{0s}=20.7$, $p_{0s}=0.0625$, $(\Delta p/\Delta v)_0=125$, $B_0=8.15$, $\Gamma_0=3745$, $E_0=2150$.
The broken line surrounds the solidified region.

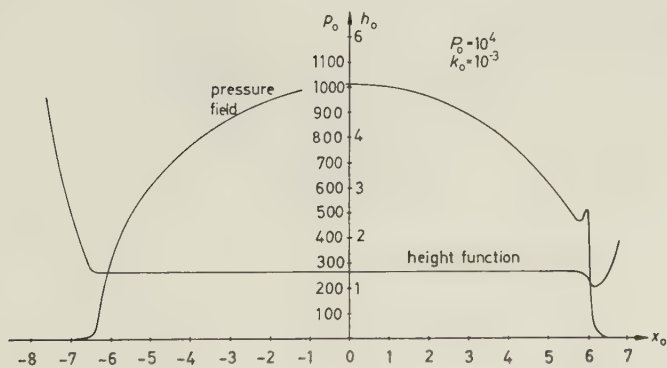


Fig. 4. Theoretical height function and pressure field for $P_0=10,000$, $k_0=0.001$, $\delta_0=0.000791$, $B_0=0.00670$, $\tau_{0s}=2980$, $p_{0s}=75.9$, $(\Delta p/\Delta v)_0=152,000$.
Power loss $E_0=220$.

Comparisons between theoretical results and experiments

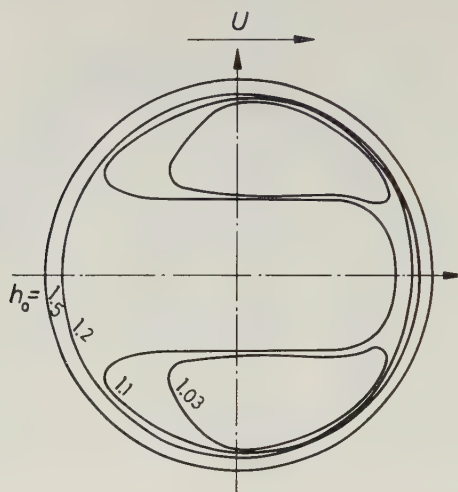


Fig. 5. Theoretical height function. $h_{\min} = -0.24 \mu\text{m}$, $k_0 = 0.1$, and $P_0 = 100$.

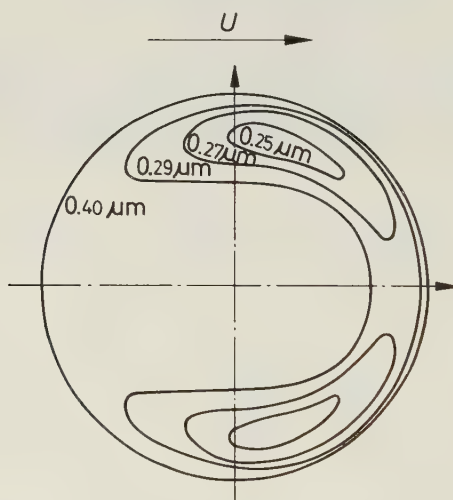


Fig. 6. Experimental height function. $h_{\min} = -0.23 \mu\text{m}$.

In figs. 5 and 6 the theoretical and experimental height functions for a ball to plate contact are shown.

In the theoretical case, the minimum oil film thickness is $h_{\min} = 0.24 \mu\text{m}$ and in the experiment $h_{\min} = 0.23 \mu\text{m}$.

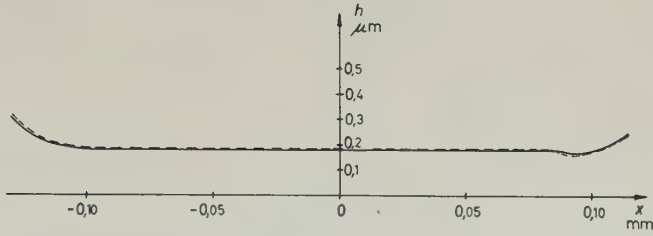


Fig. 7. Theoretical height function for $P=28 \text{ N/mm}$, $\eta_a=0.4 \text{ Ns/m}^2$, $R=5 \text{ mm}$, and $U_a=0.133 \text{ m/s}$. The dotted line gives the experimental height function.

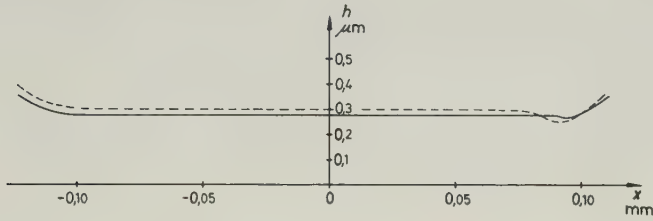


Fig. 8. Theoretical height function for $P=28 \text{ N/mm}$, $\eta_a=0.4 \text{ Ns/m}^2$, $R=5 \text{ mm}$, and $U_a=0.276 \text{ m/s}$. The dotted line gives the experimental height function.

In figs. 7 and 8 the theoretical and experimental height functions for a roller to roller contact are shown. The theoretical minimum oil film thicknesses are $0.16 \mu\text{m}$ and $0.25 \mu\text{m}$. The corresponding experimental values are $0.17 \mu\text{m}$ and $0.27 \mu\text{m}$. Theory and experiments show quite good agreement.

References

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